

**A LOW COST OPTOMECHANICAL MOUNT  
FOR PRECISELY STEERING/POSITIONING A LIGHT BEAM**

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**CROSS REFERENCE TO RELATED APPLICATION**

**[0001]** This application is a continuation-in-part of U.S. patent application Serial No. 09/906869 of Kenneth J. Wayne et al, filed on July 16, 2001, entitled "Optomechanical Mount for Precisely Steering/Positioning a Light Beam." The disclosure of co-pending application Serial No. 09/906869 is herein incorporated by reference.

**BACKGROUND**

**[0002]** Many optical systems require precision optomechanical mountings that hold optical elements in the positions and orientations required for operation of the system. To achieve proper positioning and alignment of an optical element, an optomechanical mounting generally must allow movement or rotation of the optical element relative to other optical elements during an alignment process, but once the optical element is aligned the mounting must securely hold the optical element to maintain the proper alignment during shipping and use of the optical system.

**[0003]** Figure 1 shows a prior art optomechanical mount 101, as disclosed in application Serial No. 09/906869. A sphere 105 is sandwiched between a lower spring assembly 107 and an upper spring assembly 109. The sphere 105 contains an optical element (not shown) and has openings 110 for light paths to pass through. The sphere 105 also has openings 111 that fit an alignment tool used to rotate the sphere 105 during alignment. When a cover (not shown) is clamped down over the sphere 105 and spring assemblies 107 and 109, springs (not shown) in the spring assemblies 107 and 109 apply force to keep the sphere 105 in place after alignment.

**[0004]** The optomechanical mount 101 exhibits excellent long-term alignment stability when subjected to temperature changes, shock, and vibration. However, the optomechanical mount 101 is relatively expensive to manufacture. The spring assemblies 107 and 109, in particular, have many complex parts, making the optomechanical mount 101 difficult and time-consuming to build. Therefore, it is desirable to have an optomechanical mount that maintains precise angular orientation of the optical element without requiring as many parts or as much assembly time as the optomechanical mount 101.

## SUMMARY

**[0005]** In accordance with a preferred aspect of the invention, rigid balls are used to support and apply force to a sphere containing an optical element fixed at its center. A lower set of balls supports the sphere, and an upper set of balls rests on top of the sphere.

Generally, each ball in the lower set has a corresponding ball in the upper set; each ball in the lower set applies a force to the sphere that is collinear with and opposite to a force that the corresponding ball in the upper set applies to the sphere. All ball forces are directed through the center of the sphere. As used herein, the "center" of the sphere refers to the true center of the sphere, not the center of mass. The opposing forces from the balls maintain positional stability of the sphere when the optomechanical mounting is subjected to thermal variations, vibrations, or shock. The balls and other components should be made of the same material or materials having substantially similar coefficients of thermal expansion (CTEs), so that thermal expansion of the assembly and component parts does not result in a rotation of the sphere containing the optical element. This gives the optomechanical mounting superior thermal stability.

**[0006]** The sphere and balls are enclosed within a housing and held in place by a lid. The housing preferably has cavities recessed in its base to hold the lower set of balls. The housing has openings in the center for light paths of the optical element or for access to the sphere during the alignment process. The sphere and upper set of balls are aligned in the housing on top of the lower set of balls before the lid is attached to the housing. The lid aligns the upper set of balls and applies force, such that each ball in the upper set applies a force to the sphere that is collinear and diametrically opposed to a force from a ball in the

lower set. These forces are strong enough to hold the sphere in position and to resist alignment changes due to mechanical shocks once the optomechanical mount is completely assembled. At the same time, the fine surface finishes on the sphere and the balls allow the sphere to be rotated smoothly, and with high resolution, once surface friction between the sphere and the balls is overcome.

**[0007]** In another embodiment, the sphere can be held in place by high-strength magnets. The magnetic force is sufficient to hold the sphere in alignment, yet weak enough to be overcome when the sphere is rotated with an alignment tool.

**[0008]** These embodiments require fewer parts and less assembly time than the prior art optomechanical mount 101. Therefore, the cost of manufacturing for the present invention is lower.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Figure 1 is a perspective view of a prior art optomechanical mounting, as disclosed in application Serial No. 09/906869.

[0010] Figure 2A is a perspective view of an optomechanical mounting in accordance with an embodiment of the invention.

[0011] Figure 2B is a perspective view of an optomechanical mounting in accordance with an embodiment of the invention, with the housing removed to show inside detail.

[0012] Figure 2C is a perspective view of the housing of an optomechanical mounting in accordance with an embodiment of the invention.

[0013] Figures 3A and 3B show alternate structures that can be used in place of balls to constrain the sphere.

[0014] Figure 4A shows an alternate embodiment of the present invention.

[0015] Figure 4B shows a means for applying downward force upon an alternate embodiment of the present invention.

[0016] Use of the same reference symbols in different figures indicates similar or identical items.

DETAILED DESCRIPTION

**[0017]** In accordance with an aspect of the invention, a lower and an upper set of rigid balls supports a sphere containing an optical element. The balls are substantially identical and are oriented so that each ball applies a force along a radius of the sphere. Each of these forces is collinear with an opposing force from a ball from the other set of balls. The balls accordingly hold the sphere in position with a high degree of thermal stability because the housing, sphere, and support balls are made of materials having identical or substantially similar CTEs. Therefore, the housing, sphere, and support balls all expand and contract in unison without imparting rotation to the sphere containing the optical element.

**[0018]** Figure 2A is a perspective view of an optomechanical assembly 201 in accordance with an embodiment of the present invention. A sphere 105 rests on support balls 207 in a housing 203. The sphere 105 is adapted to receive an optical element (not shown). Upper balls 209 are arranged on the sphere 105 and partially constrained by the sphere 105 and the central bore of the housing 203. A lid 211 is attached to the housing 203. The lid 211 has openings 212 that fit over the upper balls 209. Each ball in the support balls 207 has a corresponding ball in the upper balls 209. Each pair of balls is diametrically opposed from its matching mate, so that the forces exerted by each pair on the sphere 105 are equal and opposite in direction.

**[0019]** The housing 203 has openings 205 for light paths to and from the sphere 105, or to allow access to the sphere 105 during the alignment process. The housing 203 is preferably made out of the same rigid material as the balls, such as steel. Since the housing 203 has flat surfaces and is cubic in shape, it is less costly to machine and manufacture than the rounded spring assemblies 107 and 109 shown in the prior art of Figure 1.

**[0020]** Figure 2B is a perspective view of the optomechanical assembly 201 shown in Figure 2A, with the housing 203 removed so as to better illustrate the arrangement of the sphere 105, the support balls 207, the upper balls 209, and the lid 211. In the exemplary embodiment, the support balls 207 are placed so that when the upper balls 209 are in position, each one of the support balls 207 is diametrically opposed to a corresponding ball in the set

of upper balls 209. In this fashion, equal and opposite forces are applied to the sphere 105. For example, the balls 207-1, 207-2, and 207-3 can be located at 0°, 120°, and 240° in a plane normal to a vertical axis of sphere 105, while the balls 209-1, 209-2, and 209-3 are located at 180°, 300°, and 60° around another plane normal to the vertical axis. With this configuration, force vectors for a pair of balls (207-1, 209-1), (207-2, 209-2), or (207-3, 209-3) are collinear and pass through the center of the sphere 105. Each support ball 207 thus has a corresponding upper ball 209 that provides an equal, collinear opposing force through the center of the sphere 105. Accordingly, balls 207 and 209 do not apply a torque to the sphere 105, and changes in the upper balls 209, for example, caused by changes in temperature, counter or cancel corresponding changes in the support balls 207 to keep the sphere 105 from shifting position.

**[0021]** The illustrated embodiment depicts three balls in the support balls 207 and three balls in the upper balls 209 for a total of six balls. This is a preferred number of balls, since the sphere 105 is minimally constrained. However, more balls can be used. The support balls 207 and the upper balls 209 are identical in size and shape. In a working embodiment of the invention, the balls used were approximately 11.1 mm in diameter. The balls can be varied in size without affecting the functionality of the invention. The balls precisely position the sphere 105 so that the center of the sphere 105 remains in place during and after alignment.

**[0022]** The sphere 105 contains an optical element (not shown) such as a mirror, a beam splitter, a translating window, a wedge window, or a lens. Optical elements mounted in the sphere 105 can vary widely, but generally, the center of the sphere 105 lies on the optical center, which may be an optical surface, an axis, and/or a symmetry plane of the optical element in the sphere 105. In the exemplary embodiment, the sphere 105 is a precision bearing about 41.275 mm in diameter that is machined to include openings 110 for light paths to and from the optical element. The sphere 105 can further include openings 112 that fit an alignment tool such as an Allen key or lever that can be used to rotate the sphere 105 in the finished optomechanical assembly 201. Additional access ports for tooling can be provided at almost any position, notably at 45° positions in a vertical plane. The sphere 105 can be rotated about any axis running through its center. The forces exerted by the support balls 207

and upper balls 209 hold the sphere 105 in place and protect it from shocks or jars that might disturb the alignment of the sphere 105.

**[0023]** The lid 211 has openings 212, one for each of the upper balls 209. The openings 212 are narrower than the diameter of the upper balls 209, so that the edges of the openings 212 will contact the surfaces of the upper balls 209 when the lid 211 is placed over the upper balls 209. When the lid 211 is attached to the housing 203, the contact points transfer the downward force from the lid 211 to the upper balls 209, and keep the upper balls 209 in position. The lid 211 also has a central opening 210, to allow a light path or an alignment tool to access the sphere 105.

**[0024]** All of the components in the optomechanical assembly 201 can be made of the same material or materials that are substantially the same or at least have the same or similar CTEs. If the CTEs are the same, the entire assembly expands or contracts in unison when subjected to a temperature change. Thus, the sphere 105 will not rotate during acclimatization, and the angular alignment of the optical element is preserved when the temperature changes. In an actual working embodiment, stainless steel was used to make the housing 203, support balls 207, upper balls 209, sphere 105, and lid 211. However, other rigid materials, such as steel, Invar, etc. can also be used.

**[0025]** The sphere 105, support balls 207, and upper balls 209 should have surface finishes that permit rotation of the sphere during alignment. If the sphere 105, support balls 207, and upper balls 209 are all made of the same material, then it is possible that galling (microscopic cold welding) will occur between the sphere 105 and the other balls as the sphere 105 is rotated during adjustment. If the system will only be adjusted a few times, this is not a serious problem and indeed may even be an advantage because the long-term stability of the setting is improved. However, if the system will be adjusted frequently, it is preferable to reduce the surface friction between the sphere 105, support balls 207, and upper balls 209 so as to prevent galling.

**[0026]** One method of reducing surface friction, if cleanliness is not a requirement, is to lubricate the components of optomechanical assembly 201. If cleanliness is a consideration,

another option is to make support balls 207, or upper balls 209, or both sets of balls out of a material that has less surface frictional force to overcome. A ceramic such as silicon nitride is one possible material. If the primary concern is reduced surface friction and smooth adjustment for the sphere 105, a copper alloy such as brass or bronze may also be used. However, using a copper alloy may negatively impact thermal stability, durability, and shock stability.

**[0027]** Figure 2C is a perspective view of just the housing 203. The housing 203 has depressions 213 in its base. The support balls 207 (not shown) fit into the depressions 213, and are secured with epoxy, welding, press fitting, screws, or any other method of attachment. The housing 203 has a hole 215 in its base to allow access to the sphere 105 for a light path or an alignment tool.

**[0028]** To assemble the optomechanical assembly 201, the support balls 207 are set into the depressions 213 of the housing 203 and fixed in place. The sphere 105 is placed onto the support balls 207, and then the upper balls 209 are arranged around the sphere 105 as previously described. The upper balls 209 stand slightly above the top face of housing 203. Finally, the lid 211 is screwed onto housing 203 or otherwise secured over the upper balls 209. The lid 211 applies a downward spring force to each one of the upper balls 209. The magnitude of this force is fixed by the height of the ball contact points above the top face of the housing 203, the stiffness of the lid 211, and fabrication tolerances. The selection of this magnitude will depend on the shock/vibration environment. In an actual working embodiment, the force was approximately 15 to 20 pounds per upper ball 209.

**[0029]** The sphere 105 may be constrained using structures other than support balls 207 and upper balls 209. For instance, hemispheres and smaller portions of spheres can be used in the place of balls. Figure 3A shows some possible substitute structures for support balls 207 and upper balls 209. The best structures have surfaces that will contact the sphere 105 at approximately a single point. The examples shown in Figure 3A have spherical surface portions that will contact the sphere 105 at approximately a single point. The word “approximately” is used because it is almost impossible to manufacture such perfect surfaces that will contact and remain in contact with each other at exactly a single point.

**[0030]** Other structures may be used that have many points of contact with the sphere 105. Figure 3B illustrates one such example. However, these structures generate higher frictional forces and make alignment of the sphere 105 difficult. There are other well-known methods for supporting the sphere 105 that will maintain rotational freedom about any axis. For instance, using a conical surface to support a sphere is a method well known in the art.

**[0031]** Figure 4A shows an alternate embodiment of the present invention, using high-strength magnets 401 to hold the sphere 105 in place. The magnets 401 can be fixed to the base of the housing 203 (not shown) with any well-known means such as epoxy, press fitting, etc. Some possible high-strength magnets are alnico, ceramic, and rare-earth magnets. The magnets 401 are mounted so that they are slightly angled in towards the sphere 105, to facilitate contact with the surface of the sphere 105. Due to the perspective of Figure 4A, only two magnets 401 can be seen; a third magnet 401 is positioned out of sight behind the sphere 105, such that all three magnets 401 are positioned at equidistant intervals around the sphere 105. Although only three magnets 401 are shown in the figure, more than three magnets can be used.

**[0032]** The magnets 401, as drawn, are rectangular in shape, but can also be circular or any other shape. Obviously, the sphere 105 should be made of a material that will be attracted to the magnets 401. The sphere 105 is placed upon the magnets 401, and the magnetic force holds the sphere 105 in place when the sphere 105 is not being aligned. The magnets should be chosen so that their magnetic force is strong enough to keep the sphere 105 in alignment, yet weak enough to be overcome when the sphere 105 is rotated with an alignment tool. No upper magnets are needed in contact with the sphere 105, since any upper magnets would tend to pull the sphere 105 away from the magnets 401.

**[0033]** If the magnets 401 do not have enough magnetic pull on the sphere 105, it may be necessary to apply a downward force upon the sphere 105 to prevent it from lifting off of the magnets 401 during the alignment process. Figure 4B shows one possible means for applying a downward force 403 upon the sphere 105. A cover 405 for the housing 203 (not shown) has a contact 407 mounted on a spring 309. When the cover 405 is attached to the housing 203, the contact 407 pushes against the surface of the sphere 105. The spring 309

provides the downward force 403 to keep the sphere 105 from lifting off of the magnets 401 while it is being aligned.

**[0034]** Although the invention has been described with reference to particular embodiments, the described embodiments are only examples of the invention's application and should not be taken as limitations. For example, although specific dimensions and materials were described for an exemplary embodiment of the invention, those dimensions and materials are subject to wide variations and replacements. Various other adaptations and combinations of features of the embodiments disclosed are within the scope of the invention as defined by the following claims.